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CERTIFICATE

This certificate is issued in support of an application for Patent registration in a country outside New Zealand pursuant to the Patents Act 1953 and the Regulations thereunder.

I hereby certify that annexed is a true copy of the Provisional Specification as filed on 31 March 2004 with an application for Letters Patent number 532066 made by INDUSTRIAL RESEARCH LIMITED.

Dated 11 April 2005.

Neville Harris
Commissioner of Patents, Trade Marks and Designs

330 High Street, Lower Hutt
PO Box 30687, Lower Hutt, New Zealand or DX SX 11129, Wellington
Freephone: 0508 4 IPONZ (0508 447 669), International callers dial: +64 3 962 2607, Fax: +64 4 560 1691, www.iponz.govt.nz

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PROVISIONAL SPECIFICATION

COMPOSITE SUPERCONDUCTOR CABLE PRODUCED BY TRANSPOSING PLANAR SUBCONDUCTORS

We, INDUSTRIAL RESEARCH LIMITED, a New Zealand company of Brooke House, 24 Balfour Road, Parnell, Auckland, New Zealand,do hereby declare this invention to be described in the following statement:

BACKGROUND:

Many applications of high Tc superconductors (HTS), such as power transformers and high current magnets, require higher current than the capacity of presently available conductor tape. High currents can be attained by forming cables of multiple subconductors in which the individual conductors are continuously transposed such that each subconductor is electromagnetically equivalent. In this way current is equally shared and AC losses minimised. A spiral arrangement of conductors on the surface of a cylinder achieves this, but with inefficient use of space so that the overall engineering current density of the winding is reduced. The Roebel bar and Rutherford cable are transposed conductor cable configurations which combine high packing density with rectangular cross-section. The Rutherford cable has been used extensively with low Tc superconductors (LTS) (see for example, M. N. Wilson, "Superconductors and accelerators: the Good Companions", IEEE Transactions on Applied Superconductivity, Vol. 9, No. 2, June 1999, pages 111-121.) The Roebel bar is long established as a high current copper conductor for transformers and has been fabricated using HTS conductor (see J. Nishioka, Y. Hikichi, T. Hasegawa, S. Nagaya, N. Kashima, K Goto, C Suzuki, T Saitoh, "Development of Bi-2223 multifilament tapes for transposed segment conductors", Physica C volumes, 378–381 (2002) 1070–1072; V Hussennether, M. Oomen, M. Leghissa, H.-W. Neumüller, "DC and AC properties of Bi-2223 cabled conductors designed for high-current applications", Physica C 401 (2004) 135–139 and Suzuki et. al. "Strain properties of transposed segment conductors for a transmission cable", Physica C, volumes 392-396, (2003) pages 1186-1191).

In addition to the requirement for high-current conductor most AC applications of HTS demand low AC loss. In general this means that conductors should be transposed, electrically decoupled, and have minimal transverse dimensions. Because of the typically ribbon-like form of HTS conductors, it may be desirable for AC applications to manufacture conductor with narrower strand width than the usual DC conductor. An application might be, for example, in parts of windings exposed to appreciable AC fields oriented perpendicular to the face of the conductor. This narrow strand conductor will need to be made into a transposed multistrand conductor to give adequate current capacity for many applications. The shorter the transposition twist pitch, the lower the effective interstrand resistivity can be while still keeping the strands magnetically decoupled (see M. N. Wilson, "Superconductors and

accelerators: the Good Companions", IEEE Transactions on Applied Superconductivity, Vol. 9, No. 2, June 1999, pages 111-121,equation 3). Provided decoupling is achieved, lower interstrand resistivity improves electrical and thermal stability and facilitates electrical connection to the cable.

There are presently two main HTS tape conductor types in production or development. Multifilament silver or silver alloy-sheathed composite conductor using the superconducting cuprate of composition $(Bi,Pb)_{2.1}Sr_2Ca_2Cu_3O_x$ (otherwise known as Bi-2223) is produced in commercial quantities by a powder-in-tube (PIT) manufacturing process involving drawing, rolling, and thermal treatment processes. A typical conductor will consist of approximately 55 HTS filaments embedded in a silver or silver alloy matrix, will have a cross-section of about 4 mm by 0.2 mm and a critical current at 77 K in self-field of up to 150 A.

Roebel-type cabled conductor made from PIT conductor has been disclosed in the literature (see J. Nishioka, Y. Hikichi, T. Hasegawa, S. Nagaya, N. Kashima, K Goto, C Suzuki, T Saitoh, "Development of Bi-2223 multifilament tapes for transposed segment conductors", Physica C 378–381 (2002) 1070–1072; V Hussennether, M. Oomen, M. Leghissa, H.-W. Neumüller, "DC and AC properties of Bi-2223 cabled conductors designed for high-current applications", Physica C 401 (2004) 135–139). A method for forming Roebel bar cable by controlled bending of tapes of this type is described in C Albrecht, P Kummeth, P Massek, "Fully transposed high Tc composite superconductor, method for producing the same and its use" US Patent Application US 2003/0024818 A1, Publication date Feb. 6, 2003. This takes account of the sensitivity of PIT tape to deformation-induced damage by imposing minimum limits on the edge-wise (i.e. in the plane of the tape) bending radius and bending zone length respectively of 100 times and 20 times the tape width. The resulting cable pitch for complete transposition is comparatively long.

In contrast, coated conductor composite (CCC) is produced as a thin film of $YBa_2Cu_3O_7$ (Y-123) approximately 1 μm thick on a substrate of a base metal tape coated with various oxide films (see for example A. P. Malozemoff, D. T. Verebelyi, S. Fleshler, D. Aized and D. Yu "HTS Wire: status and prospects", Physica C, volume 386, (2003) pages, 424-430). Although CCC is currently produced in 1cm wide tape, manufacture will ultimately be scaled up to tape 10 cm wide or more.

Methods have been developed for laminating CCC with copper tape to protect the tape from thermal-electrical instability and, by locating the HTS film at or near the neutral axis for flat-wise (out-of-plane) bending, from mechanical stress. It is envisaged that standard conductor with around 4 mm width will be slit from the wide conductor. Edge-wise bending of CCC tape to form cables will, like PIT tape, be subject to limits on the minimum bending radius. There is, at present, no published data on the sensitivity of CCC tape to edge-wise bending. However, due to its different mechanical properties compared with silver and silver-alloy sheath material one might expect even more difficulty in edge-wise deformation.

The prospect of manufacturing CCC in wide tapes able to be slit to give multiple narrower subconductors allows for novel means of forming transposed conductors with a short transposition pitch.

OBJECT OF THE INVENTION

The present invention relates to the forming of high current and/or low AC loss transposed conductor from CCC tape or similar coated conductor without the need for substantial in-plane deformation by cutting the periodic, serpentine shape required for the transposed conductor from a wider tape. The required number of strands of this serpentine subconductor are then assembled using a planetary winder with appropriate lengthwise displacement of each subconductor in cyclic order to form a transposed conductor. The cable is then treated to fix the individual subconductors in their place for subsequent handling, manufacturing, and implementation operations, preferably using methods which optimise the interstrand resistivity to achieve low AC loss.

It is an object of this invention that many parallel serpentine conductors may be cut out from a single strip as illustrated, for example in figure 5, such that wastage may be minimized. It is also possible that the substrate tape is precut or partially precut before formation of the superconducting layer and all or some of any buffer layers to facilitate separation of the subconductors with minimal damage to the superconducting properties.

The superconductor element may for example, consist of a thin layer of YBCO or other cuprate superconductor which is epitaxially grown on a substrate or other forms of non-epitaxial HTS which might be deposited on base metal substrate tapes in excess of 1 cm wide.

The substrate consists of a metal tape which may be coated with single or multiple buffer layers. The metal tape may, for example, be textured or non-textured nickel or nickel alloy or Hastelloy. The buffers may be textured through epitaxy with the textured metal tape or textured independently through "Ion beam assisted deposition" or "Inclined substrate deposition". On top of the superconductor layer may be deposited a noble metal cap layer and / or copper stabilisation layer. Two such tapes may be joined "face to face" to form a composite with two superconducting layers in a single element.

The CCC tape might be, for example, manufactured in 10 cm width, laminated on the HTS face with a copper or alloy stabiliser tape, and cut into multiple subconductor strands of the desired serpentine shape using mechanical slitting, or laser or fluid jet cutting or other known means.

Each strand may be of thickness 50 microns to 500 microns with a typical thickness of 100-200 microns. Each strand may be of average width 200 microns to 10 mm, with a typical average width of 1 mm to 2 mm. The strands have a rectangular or near rectangular cross sectional shape.

Coating with copper or other metal or alloy layer or layers using electroplating or other means could be carried out before or after cutting depending on the need for hermetic protection of the edge of the HTS layer. The mechanical properties and thickness of the stabiliser and any plated layers would preferably be selected to locate the HTS film at the mechanical neutral axis so that out-of-plane bending of the composite conductor with a small radius of curvature could be tolerated without damage.

Two cases may be distinguished, by way of examples:

In the case of a Rutherford cable type transposition the shape to be cut is of the general form shown in Fig.1a; a zigzag. Straight portions at the turning sections at the edges may be added as in Fig.1b. The bend required for the vertical transposition by one tape width is accommodated in the turning sections. The transposition of the subconductors to form the cable is performed with a planetary winding system of the type well established in the cable winding industry. Fig.2a depicts the layout of a 4-strand Rutherford cable. The cable may be wound with or without a resistive core separating the two layers of the cable as shown in Fig.2b. The use of a resistive core is well known in the field, see for example, J D Adam et al, "Rutherford cables with anisotropic transverse resistance", IEEE Transactions on Applied Superconductivity, Vol. 7, No. 2, June 1997, 958-961). The core may have a thickness of 25 microns to 1mm and typically will have a thickness of 50 microns. The core will preferably be of a non magnetic metal alloy.

In the case of a Roebel bar type transposition the shape to be cut would be of the form shown in Fig.3, namely alternating relatively long straight portions with a short interval of cross-over between the two. The cross-over sections may have a sinuous shape (for example with the edges following a sinusoidal path) rather than the straight –sided cross-overs shown. However, for the same length of cross-over, more sinuous shapes will have a more constricted cross-section and are not favoured on account of the reduced local current carrying capacity.

The layout of a Roebel-type cable is shown in Fig.4. Neglecting any material wasted along the margins of the cuts, subconductor of this shape can be cut with the wastage of only one track width from the parent tape, as depicted in Fig.5. For example, only 4% would be discarded in the case of 4 mm track width and 10 cm manufactured width. Appropriately spaced out-of-plane bends, as may be required for the vertical cycling of the subconductors in the Roebel bar stacks if the conductor faces are to be maintained parallel to the cable axis, can be accommodated with a radius of curvature of a millimetre or less provided the HTS film is located near the neutral axis of the composite. Planetary winding equipment would again be used to transpose the conductor.

The shape for the pre-cut strands is chosen so as to provide as uniform as possible a superconducting cross section. Straight sections are to be preferred over sinuous profiles for this reason. The superconducting current will be limited by the region with minimum cross section. At the same time the utilisation of as much as possible of the original superconducting sheet is also desirable.

Each cable may contain 2 – 100 strands, with a typical cable containing 5-40 strands.

The transposition length is determined by the number of strands. In the case of a Roebel-type cable of N subconductors the transposition length L is given by

$$L = N(C + D)$$

Where C is the length of the cross-over section of the subconductor profile and D is an allowance for out-of-plane bends or relative displacement of the subconductors required to assemble the cable without excessive twisting of individual strands.

The method described for forming Roebel and Rutherford type cables is compatible with fully insulated subconductors or with more or less conductive or resistive material bonding the subconductors together and providing electrical connectivity as required for optimal electromagnetic decoupling, electrical stabilisation, and for transfer of current at splices and contacts. For example, the subconductors may be electrically connected and bonded by solder or by the heat treatment of copper or other metallic coating to produce an oxide layer with optimal resistivity.

In a preferred form each strand will have an adherent, continuous, high resistivity coating preferably with a thickness range of 1 micron to 5 microns. The high resistivity coating may for example, be formed from sol-gel deposition or decomposition of a metal organic solution. As a further example, the high resistivity coating may be formed from oxidation of a precursor metal layer. The oxidation must be controlled so as not to oxidise the copper stabilisation layer in contact with the superconducting layer. The precursor metal layer may for example, be formed by electroplating, physical vapour deposition, or electroless plating.

The final cable may for example, be heat treated so that the high resistivity coating of each strand is diffusion bonded to a neighbouring strand.

The high resistivity oxide coating may be an oxide of a transition metal, including tin, bismuth, gallium, antimony, zinc, iron, nickel, niobium, tantalum, zirconium and/or indium or alloys therof with each other. The oxide coating has a preferred resistivity of greater than about 10 microohms cm.

The invention is further described by the following figures in which:

Figure 1 shows the zigzag pattern to create the Rutherford type cable. The cable width is W and the conductor width is B. L is the transposition distance for the cable. The simplest pattern is shown in (a). This pattern can be varied, such as shown in B, without altering the object of the invention.

Figure 2 shows A) A top view of the Rutherford cable formed from the serpentine strand of figure 1. The dashed lines show obscured parts of the tape. The shaded region shows the continuity of a single strand with the lighter shaded regions obscured. B) The Rutherford cable with former positioned between the top and bottom layers.

Figure 3 shows the serpentine shape required to create the Roebel type cable. The cable width is 2 x B_1. The conductor width is B_1 in the straight sections and B_2 in the crossover sections. The transposition length of the cable is L.

Figure 4 show the assembled Roebel type cable. The conductor thickness is d and the transposing pitch is P.

Figure 5: The pattern of cuts on a wide CCC tape to make serpentine strands for Roebel type cable. Shaded areas show waste material. G is the width of the manufactured conductor sheet.

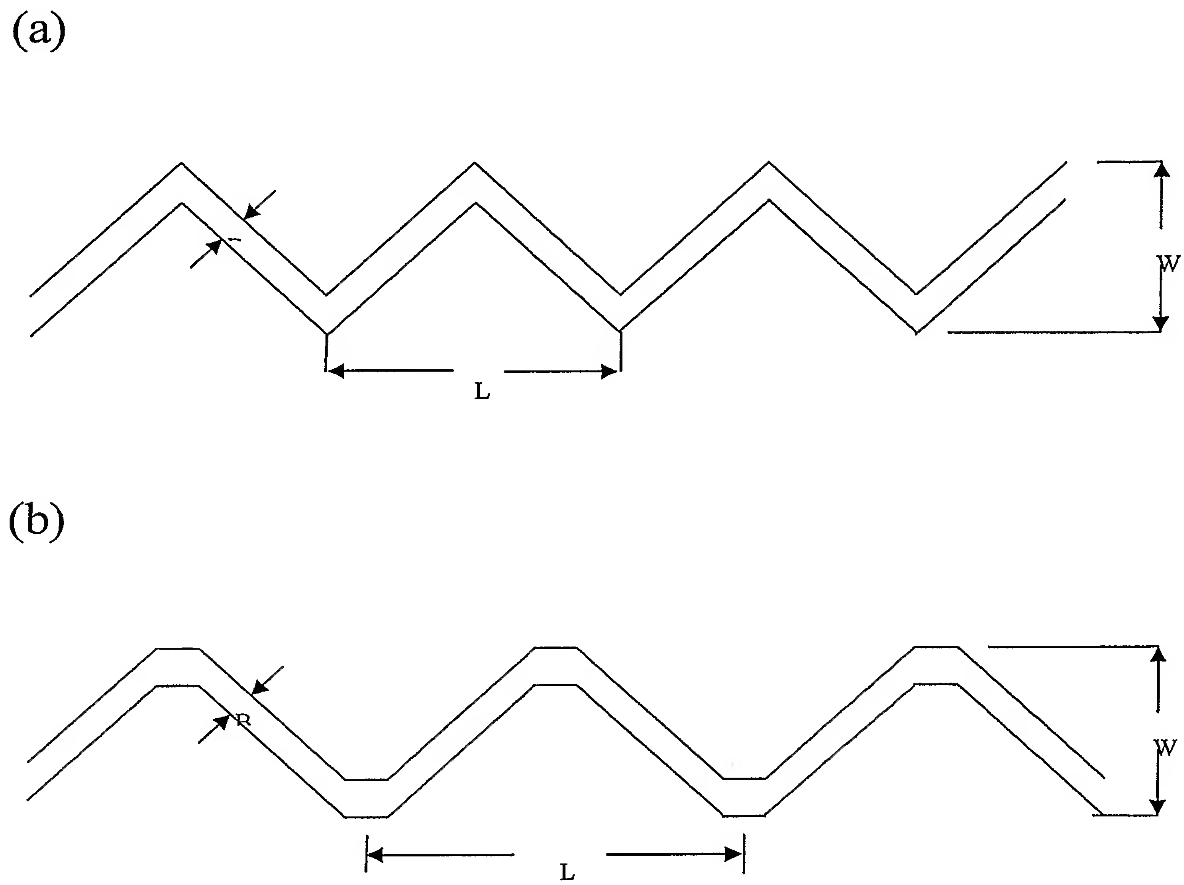
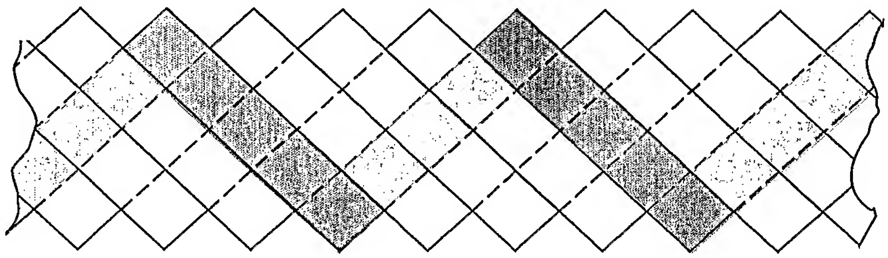


Figure 1

(a)



(b)

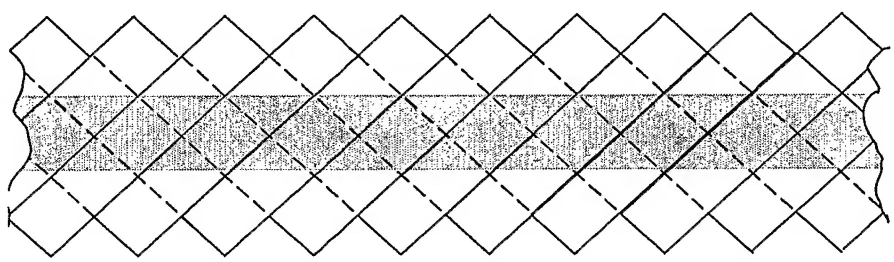


Figure 2

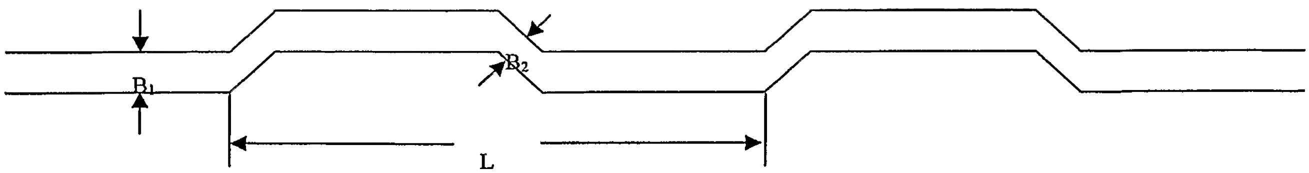


Figure 3

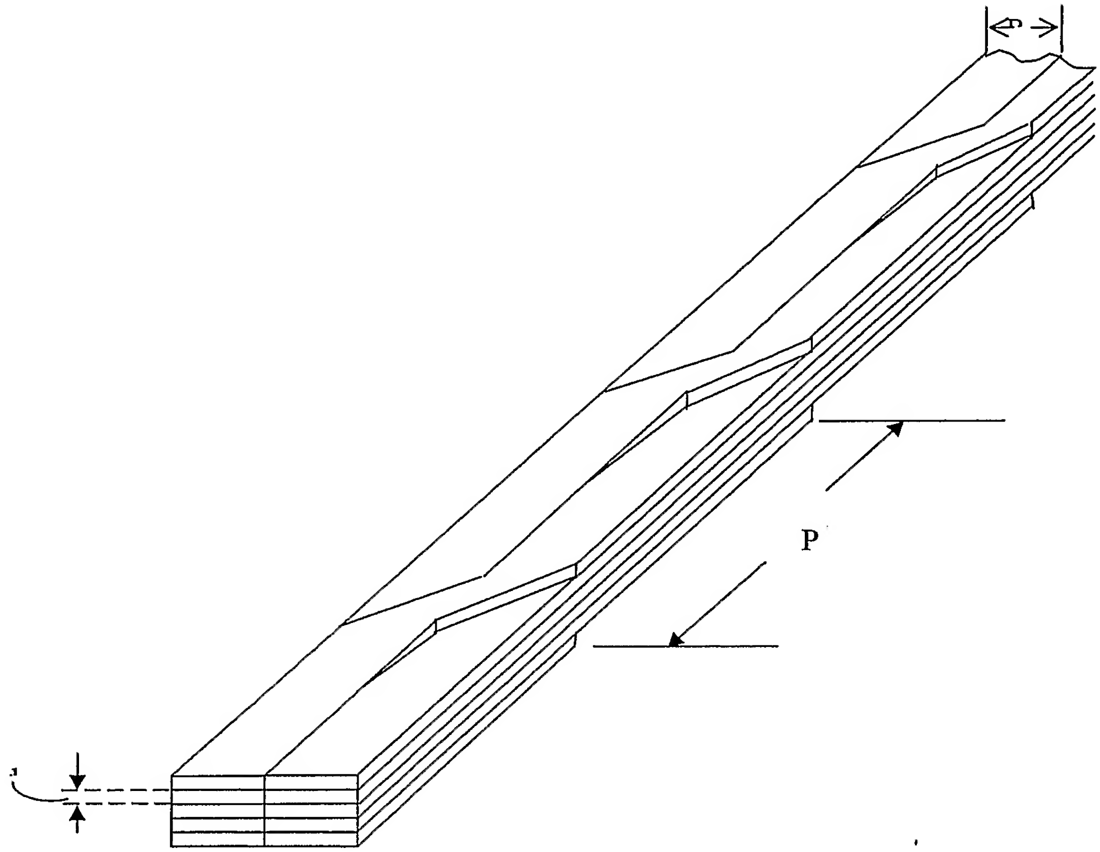


Figure 4

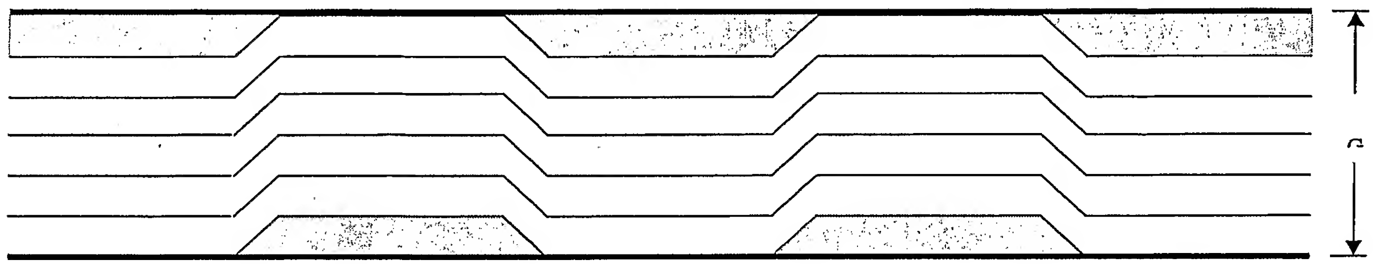


Figure 5